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Future projections of active-break spells of Indian summer monsoon in a climate change perspective

B.L. Sudeepkumar[a,c], C.A. Babu[a,*], Hamza Varikoden[b]

[a] Department of Atmospheric Sciences, Cochin University of Science and Technology, Cochin 682 016, India
[b] Indian Institute of Tropical Meteorology, Pashan, Pune 411 008, India
[c] India Meteorological Department, Lucknow 226 009, India

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A B S T R A C T

The effect of global climate change on Indian summer monsoon has been analysed with special emphasis on active-break cycle. The changes in intensity and duration of active and break monsoon conditions towards the end of the century are studied by using 850 hPa zonal circulations. The analysis is carried out using twenty year climatology of historical period (1986–2005) and future projections (2080–2099) simulated as part of Coupled Model Intercomparison Project phase 5 (CMIP5). Models are compared with NCEP/NCAR reanalysis data. The models that effectively capture the circulation pattern of monsoon (JJAS) are considered for assessing the future climate in RCP 4.5 scenario. They are CanESM2, CNRM-CM5, GFDL-ESM2M, MIROC5 and MPI-ESM-LR. During the southwest monsoon period, the ensemble mean of models projects a strengthening of the wind speed towards north (north of 15°N) and weakening to the southern region (especially south of 12°N) which facilitates wetting of northern Indian regions and drying of southern peninsular regions. In the case of active-break conditions, the active spells are found to be strengthening over northern India and weakening over the peninsular India, the break spells intensify over southern tip of peninsular India indicating intense breaks. Increased propensity of short intense active days and decreased propensity of long active days are also projected by the models. The number of break spells does not show any significant changes.

1. Introduction

Indian summer monsoon (ISM) is associated with different large scale features that affect lives of millions of people across South Asia. The summer monsoon rainfall has a remarkable regularity and provides 75–90% of the total annual rainfall in the country. All the crucial fields in India including agriculture, industrial and economy directly or indirectly depend on the Indian summer monsoon rainfall (Mooley et al., 1981; Mooley and Parthasarathy, 1982). The variability of summer monsoon rainfall alters the national gross domestic production (GDP) by affecting various factors such as water resources, agriculture, ecosystem, health and food security (Webster et al., 1998; Gadgil and Gadgil, 2006; Turner and Annamalai, 2012). Climate change has affected ISM by changing the rainfall pattern as well as modulating the circulation pattern (Dash et al., 2009; Joseph and Simon, 2005; Sreekala et al., 2014; Guhathakurta et al., 2011). One of the important studies in this context is by Joseph and Simon (2005). They reported a significant decreasing trend for mean wind strength through India (between latitudes 12.5°N and 17.5°N) during the summer monsoon season (June to September) from surface to 1.5 km altitude, and a significant increasing trend between 2.5°N and 7.5°N during 1950 to 2002. In the last two decades many modelling studies addressed the impact of climate change due to anticipated increase in greenhouse gas concentrations. It was suggested an intensification of Indian summer monsoon rainfall (Meehl and Washington, 1993; Hu et al., 2000; May, 2004; Cherchi et al., 2011; Kumar et al., 2011) and weakening of both the cross equatorial monsoon flow and tropical large scale overturning circulations in future (Kitoh et al., 1997; Tanaka et al., 2005; Ueda et al., 2006; Stowasser et al., 2009; Krishnan et al., 2013). The intensification of monsoon precipitation due to greenhouse warming was attributed due to the tropospheric warming and increase in atmospheric moisture (Meehl and Washington, 1993; Kitoh et al., 1997; May, 2004; Turner et al., 2007). The two opposite trends of rainfall and wind is called precipitation-wind paradox (Ueda et al., 2006). Studies based on observed datasets show that the distribution and frequency of rainfall are changing (Kumar et al., 1992; Goswami et al., 2006; Guhathakurta and Rajeevan, 2008; Rajeevan et al., 2008; Guhathakurta et al., 2011; Ghosh et al., 2012; Singh et al., 2014). Goswami et al. (2006) indicated a significant rising trend in the frequency and the magnitude of extreme rain events and a decreasing trend for moderate rain events over central

* Corresponding author.
E-mail address: babuca@cusat.ac.in (C.A. Babu).

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Table 1
Criteria used for classifying active and break days and different classes of spells.

Active Day: Day with area averaged zonal wind speed at 850 hPa over the domain (10°N–20°N; 70°E–80°E) > 15 m s^{-1}.	Break Day: Day with area averaged zonal wind speed at 850 hPa over the domain (10°N–20°N; 70°E–80°E) < 9 m s^{-1}.
Short active spell: Consecutive active days less than or equal to 3 days. Medium active spell: Consecutive active days > 3 days but < 7 days. Long active spell: Consecutive active days more than or equal to 7 days.	Short break spell: Consecutive break days less than or equal to 3 days. Medium break spell: Consecutive break days > 3 days but < 7 days. Long break spell: Consecutive break days more than or equal to 7 days.

India during the summer monsoon season. Singh et al. (2014) analysed two periods of the observed records (1951–1980 and 1981–2011) and demonstrated statistically significant changes in the extreme wet and dry spells in the recent decades.

All the aforementioned studies focused on the monsoon in seasonal or longer time scales or the number of rainy days. However, the sub-seasonal variations such as active-break cycles have equal or more importance to the local population. During 'active' period heavy rainfall occurs over most part of the country and scanty rainfall during 'break' period over most part of the country except along the foothills of Himalayas and southeast peninsula, there it increases. Krishnamurthy and Shukla (2000) described the interaction between seasonal mean rainfall and active-break events. It has been found that major difference between some good monsoon and some poor monsoon seasons were the occurrence of long dry spells (break) in the poor monsoon seasons (Krishnamurti and Bhalme, 1976). Heavy rainfall in short period causes flood and prolonged break condition leads to drought (Joseph et al., 2009). A significant number of break spells (~5) lasted for ≥ 10 days can have a large impact on the agricultural production of India (Gadgil et al., 2003). In this context, study of ISM focusing active-break events is indeed necessary to get a clear picture of the intensity and duration of rain events in the future. Current study is an attempt on this milieu.

Coupled Model Inter comparison Project phase5 (CMIP5) has been released in preparation of the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (IPCC- AR5) provide a range of simulated climate futures which can be used as the basis for exploring the climate change impacts and making policies relevant to society. Prior to CMIP5, its earlier version (CMIP3) has been widely utilized to study the changes associated with monsoon rainfall (Annamalai et al., 2007; Kripalani et al., 2007; Bollasina and Nigam, 2009). Then CMIP5 (Taylor et al., 2012) simulations have been released with several improvements in terms of physics and resolution. Ma and Yu (2014) described the precipitation-wind paradox based on 18 CMIP5 models with RCP 4.5 (representation concentration pathway) scenario and projected the weakening of the upper tropospheric circulation and strengthening of the low level winds. Other studies also suggested similar trend in the monsoon circulation (Tanaka et al., 2005; Ueda et al., 2006; Hu et al., 2000). The studies dealing with monsoon prediction and simulation using Global Climate Models (GCMs) (Fennessy et al., 1994; Liang et al., 1995; Sperber and Palmer, 1996; Lal et al., 1997; Soman and Slingo, 1997; Goswami, 1998; Martin, 1999; Sperber et al., 2000) focused mainly on seasonal or longer time scales. They have given less consideration to the variations in the subseasonal scale which is equally important as the seasonal scale. We try to fill the information gap regarding the subseasonal variations in terms of active-break cycles. In the first step, we assess the performance of CMIP5 models, which are simulating the mean monsoon as well as the subseasonal variation. We project the changes in low level circulation pattern towards future (2080–2099) based on RCP 4.5 scenario considering different classes of spells such as short, medium and long spells. Section 2 describes the data and methodology adopted for the study. Results and discussion are given in Section 3 and we conclude the results in Section 4.

2. Data description and methodology

Active-break cycle is the most important intraseasonal variability of the southwest monsoon (Rao, 1976). In the current study, classification of active and break days during the southwest monsoon period is made based on the criteria suggested by Joseph and Sijikumar (2004). They classified active and break spells based on 850 hPa zonal wind speed over the region 10°N–20°N; 70°E–80°E. They studied the relationship between Low Level Jet stream (LLJ) and the active-break cycle of the summer monsoon and found that during active (break) monsoon period, the core of the LLJ passes through the peninsular India (southern tip of peninsular India), which leads to enhanced (suppressed) rainfall over Indian subcontinent. The normalized anomaly of the rainfall over monsoon core zone (roughly from 18°N to 28°N and 65°E to 88°E) is found to be exceeding 1 (less than − 1) during active (break) events (Rajeevan et al., 2010). The zonal wind at 850 hPa in the domain from 1st July to 31st August (peak monsoon months) is considered to identify active and break days. The criteria opted for selection of active and break days is given in Table 1.

According to Webster et al. (1998), the duration of the break spell is generally varying from 1 to 7 days with 90% of the breaks being of 3–5 days duration, whereas according to Ramamurthy (1969) and Gadgil and Joseph (2003), over 30% of break spells last for 7 days or longer. Rajeevan et al. (2010) found that breaks events has a longer life span that of active events. According to their study, 80% (40%) of the active (break) spells were short duration and 9% (32%) were for a week or longer duration. They also found that there is a major difference between weak break spells and long intense break. Weak spells are characterized by weak moist convective regimes and long intense break have circulation pattern similar to that before the onset of monsoon. In regard to these studies, we classified active and break spells according to their duration (Table 1).

Historical data of 20 CMIP5 models for the twenty year period from 1986 to 2005 and future projection data at the end of the century (2080–2099) of the selected CMIP5 models have been used for the study. Details about the CMIP5 and its properties are given in Taylor et al. (2012). A comparison of zonal wind at 850 hPa has been made between the CMIP5 and NCEP/NCAR reanalysis data sets during the southwest monsoon period (June to September). A comparison between zonal wind at 850 hPa and all India rainfall (0.25° × 0.25°) procured from India Meteorological Department (Pai et al., 2014) is also carried out. A brief description of the CMIP5 models considered for the present study is given in Table 2. Taylor diagram is used for the evaluation of the models based on the pattern correlation and normalized variance (Taylor, 2001). The aim of this representation is to provide a comprehensive summary statistics of the model performances. IPCC AR4 panel suggested that the mean climate of a model can be constructed based on the last 20 years of the historical run (Kripalani et al., 2007). Therefore, we used historical data sets of the GCMs during 1986 to 2005 period. The models with realistic simulation for mean monsoon circulations at 850 hPa are selected for studying modulations in the future projections. Future projection of the selected models from 2080 to 2099 in Representation Concentration Pathway (RCP) 4.5 in one realization (r1i1p1) is studied. These models provide various lengths of simulations with the future radiative forcing stabilized at 4.5 W m^{-2} at the end of 21st century (Thomson et al., 2011). The change in intensity of different active-break classes at the end of the 21st century have been brought out.

Table 2
Details of CMIP5 models used for the study.

Model	Institution	Horizontal resolution (lat × lon)
BCC-CSM 1.1	Beijing Climate Center, China Meteorological Administration, China	T42L26
CanESM2	Canadian Center for Climate Modeling and Analysis, Canada	T63L35
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China	T42L26
CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France	T127L31
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence, Australia	T63L18
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory, USA	2° × 2.5° L24
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, USA	2° × 2.5° L24
INM-CM4	Institute for Numerical Mathematics, Russia	1.5° × 2.0° L21
IPSL-CM5A-LR	Institute Pierre-Simon Laplace, France	1.875° × 3.75° L39
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M), Germany	T63L47
CMCC-CESM	Centro Euro-Mediterraneo sui CambiamentiClimatici, Italy	T31L19
CMCC-CMS	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	T63L95
HadGEM2-CC	Met Office Hadley Centre, UK	N90L60
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental studies, and Japan Agency for Marine Earth Science and Technology, Japan	T85L40
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental studies.	T42L80
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental studies.	T42L80
MRI-CGCM3	Meteorological Research Institute, Japan	T159L48
NorESM1-M	Norwegian Climate Centre, Norway	1.875° × 2.5°
CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	T159L31
MRI-ESM1	Meteorological Research Institute, Japan	T159L48

3. Results and discussions

3.1. Selection of models

Climate models in CMIP5 are from different agencies and organizations across the globe. They can be different in many aspects. Hence it is necessary to identify the models which effectively capture the circulation features over Indian region. We considered 20 different climate models of CMIP5. The daily climatology of 20 models during the monsoon season (1st June to 30th September) of 1986 to 2005 is used as the historical period for understanding the seasonal cycle of the models (Fig. 1). Low level zonal wind at 850 hPa (hereafter called LZW) is one of the semi-permanent systems of the southwest monsoon. The coupled models have wind as a primary parameter and rainfall as the secondary parameter. The projection of Indian summer monsoon rainfall by CMIP5 models is not reliable as it projects unrealistic local convective precipitation often not in tune with other large-scale variables (Sabeerali et al., 2015). Sperber et al. (2013) found that most CMIP5 models have greater errors in simulating the seasonal rainfall of Indian monsoon, however, the simulation of winds have greater fidelity. Hence the LZW is a better tool to evaluate model performance in simulating monsoon. It gives a better indication of the intraseasonal variation and strength of monsoon circulation. The LZW is peaking during the months of July and August in most of the models similar to the reanalysis zonal wind (Fig. 1). All India rainfall also peaks during the same period. Four models from the 20 CMIP5 models have been filtered out (INM-CM4, IPSL-CM5A-LR, MRI-CGCM3 and MRI-ESM1) due to their poor performance in simulating the temporal variation. The models that capture the temporal variation of LZW has good spatial simulation as well (figure not included).

The efficiency of remaining 16 models in simulating LZW over the different parts of India is studied by comparing with NCEP/NCAR reanalysis LZW during the period 1986 to 2005 using Taylor diagram (Fig. 2). It gives a quantitative measure of comparison of the spatial

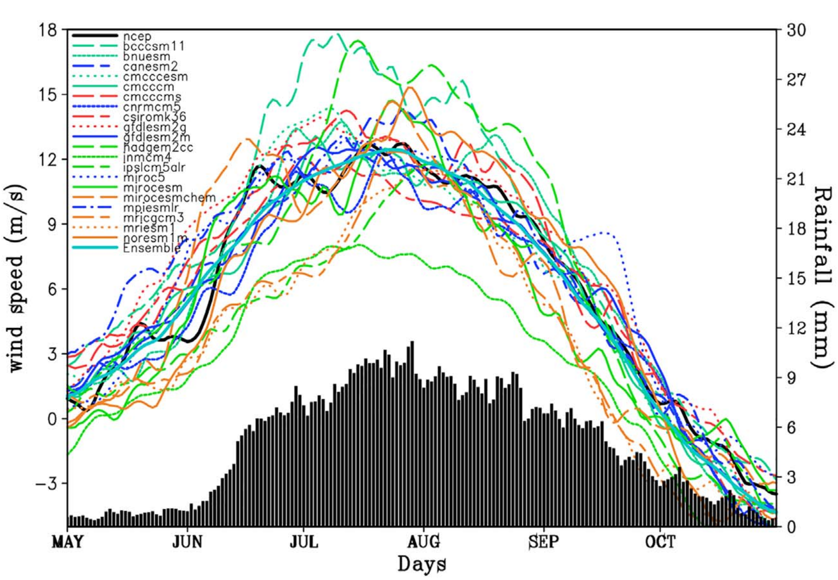

Fig. 1. Daily climatology of zonal wind speed (m s^{-1}) at 850 hPa of NCEP/NCAR reanalysis and CMIP5 models over 10°N–20°N, 70°E–80°E (line graph) and daily climatology of All India rainfall (bar graph) from 1986 to 2005.

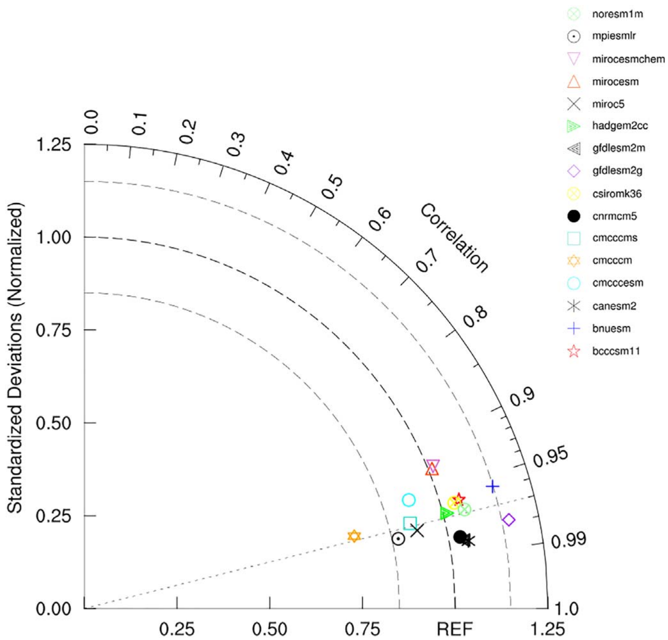

Fig. 2. Taylor diagram of 850 hPa zonal wind climatology of models during June to September over the area (40°E–100°E, 20°S–30°N).

pattern of models with reanalysis data by means of correlation coefficient and normalized standard deviation. All models possess significant correlations with the reanalysis, but varying normalized standard deviation. We selected the models giving preference to the correlation values and the models that exhibit normalized variance close to 1 (normalized variance close to 1 indicates that it is closer to reanalysis). Models having correlation coefficient > 0.97 (99.99% confidence level) and normalized variance between 0.85 and 1.15 are selected for further analysis. Based on this, we selected five models out of 16 models which capture the average spatial pattern of low level monsoon circulation. The selected models are CanESM2, CNRM-CM5, GFDL-ESM2M, MIROC5 and MPI-ESM-LR.

3.2. Projected changes in monsoon circulation

The changes expected in the monsoon LZW towards the end of the twenty first century have been studied using the future projection of the selected 5 models in RCP 4.5 scenario. Earlier studies of monsoon rainfall projected an intensification towards the end of the century (Meehl and Washington, 1993; Hu et al., 2000; Bhaskaran et al., 1995; May, 2004; Meehl et al., 2007; Kumar et al., 2011) and weakening of both the cross equatorial flow and tropical large scale overturning circulations in response to greenhouse warming (Kitoh et al., 1997; Tanaka et al., 2005; Krishnan et al., 2013). The present study focuses the change in the intensity and spatial variation of LZW during southwest monsoon period in response to global warming scenario.

Fig. 3 depicts the mean daily values of LZW over peninsular India (10°N–20°N, 70°E–80°E) during the southwest monsoon period. The solid line indicates the values of historical and dashed line is future projections in the RCP 4.5 scenario. In the future and historical simulations, the LZW of ensemble mean follows similar pattern till the mid of July. Thereafter, a decline in the wind speed is noticed in the future projections till the mid of August. During the peak monsoon month, the wind speed decreases to about 1 m s^{-1} and this indicates reduction in monsoon flow at lower levels and thus the moisture supply to the continents affect adversely the southwest monsoon rainfall. The models CanESM2, CNRM-CM5 and MIROC5 project a marked decrease in the LZW during the peak monsoon months, whereas the models GFDL-ESM2M and MPI-ESM-LR do not show any consistent trend during the peak monsoon months. The rest of the periods do not considerably influence the modulation of LZW.

Fig. 4 is the mean LZW during the southwest monsoon period during historical, future and their difference for all the selected models along with their ensemble mean. The stippled pattern in the panels of difference indicate significant at 90% confidence level based on the *Student-t*-test. Significant area of ensemble mean (where the magnitude of the ensemble mean exceeds the standard deviation of inter-model spread) also indicated in stippled pattern (Lee and Wang, 2014). From the figure, it is clear that all the selected models realistically reproduce the LZW structure in the spatial domain for both the historical and future projections. The difference figure (third column) shows that a strengthening of wind speed towards north (north of 15°N) and a remarkable weakening over the southern region (especially south of 12°N). Sandeep and Ajayamohan (2015) reported a shift in the LLJ (low level jet stream) core towards north due to the enhanced land sea contrast in the global warming scenario and thus it favours a drying in the southern region and wetting in the northern region. In concurrent with their findings, the present results also show a decrease in wind speed over southern region to facilitate drying and enhance in the wind speed over northern region conducive for wetting of the southwest monsoon in the northern region. Most of the models produce almost similar pattern however, the model MPI-ESM-LR shows an increase in wind speed over the Indian subcontinent. The maximum increase in wind strength over the Arabian Sea is noticed in the climate models MIROC5 and CanESM2. In the ensemble mean, a slight decrease in LZW at the LLJ core region (about 0.5 m s^{-1}) is observed. Towards north of the LLJ core axis, the wind speed increases maximum over the northern Arabian Sea by about 1 m s^{-1}.

3.3. Change in intensity of active and break spells

Study of change in intensity of active and break days associated with the displacement of LZW is carried out using the selected models with their ensemble mean. The spatial structure of LZW during active days for the historical and projection period is given in Fig. 5. Statistically significant regions in ensemble mean and difference (confidence at 90% level) are indicated with stippled pattern. All the models and their ensemble mean clearly show that the wind core passes through the peninsular India during both the historical and future scenarios as depicted by the studies of Joseph and Sijikumar (2004). During active days, the zonal wind shows a shift towards north as explained in the mean structure of wind pattern. However, during active days, the wind strength is higher while comparing to the mean pattern. The ensemble mean of selected models projects an increase in the strength of westerlies about 1 m s^{-1} to the north of 15°N and a decrease in the strength of westerlies to the south of 12°N. This decrease is mainly to the south of peninsular region indicating of less activity of organized convections due to formation of anticyclonic vorticity over the southern peninsular India. Due to increased wind strength over the northwest region, the northern west coast receives enhanced precipitation due to surplus moisture at the end of the century. All the five models and their ensemble mean give almost consistent result during active monsoon condition. Out of these, three models (CanESM2, GFDL-ESM2M and MIROC5) show significant results (with 90% confidence level) whereas for CNRM-CM5 and MPI-ESM-LR the results are insignificant.

In the case of break spells, the LZW bypasses through southern tip of peninsular India and Sri Lanka (Fig. 6). During break phase, the core region of LZW is shifting slightly towards west while comparing with active condition. At the end of the century, the wind strengthens towards the north over the Arabian Sea as the manifestation of the northward shifting of LLJ as explained by Sandeep and Ajayamohan (2015). A significant (with 90% confidence level) strengthening of zonal wind is noticed over southern peninsular India indicating the intensity of breaks. In the monsoon core region, the wind shows a decrease of about 1 m s^{-1}, this reduction of wind over the central India or

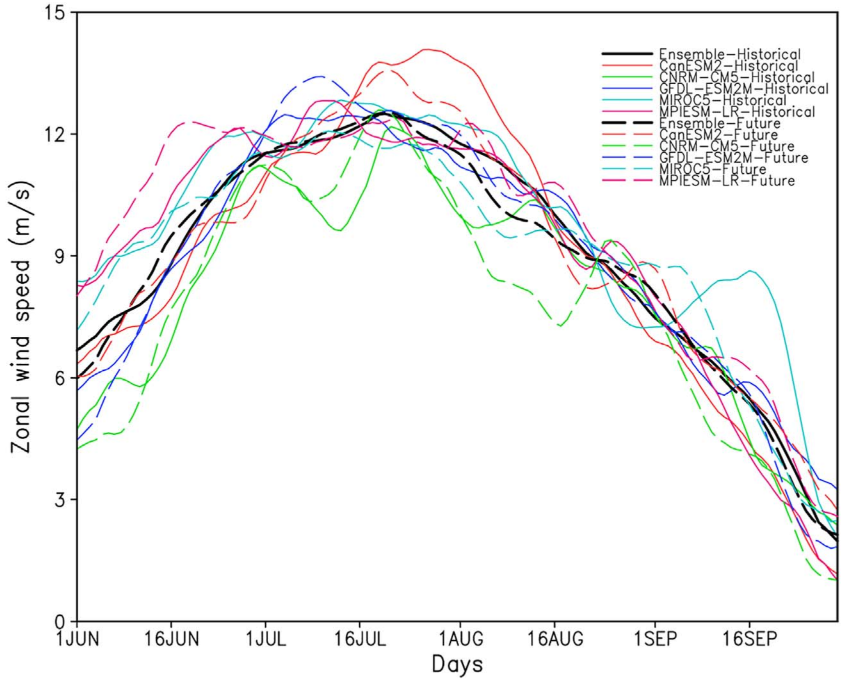

Fig. 3. Daily march of area averaged wind speed of the ensemble mean and models over the area 10°N–20°N, 70°E–80°E during June to September. Solid line indicates for the historical scenario (1986–2005) and dashed line for future scenario (2080–2099).

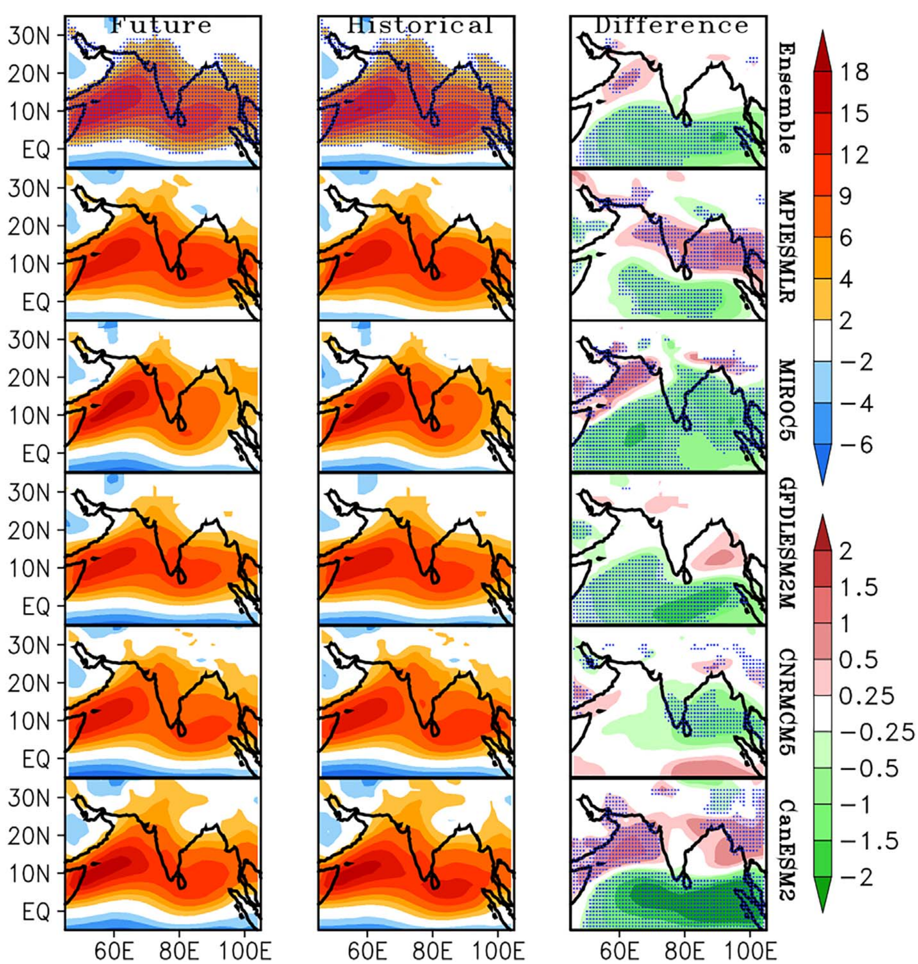

Fig. 4. Climatology of 850 hPa zonal wind (m s^{-1}) of ensemble and models during June to September. Future: 2080–2099, historical: 1986–2005, Difference: [U wind (future) – U wind (historical)]. Stippled pattern indicates significant area.

monsoon core regions is a clear indication of further decrease of monsoon rainfall at the end of the century during break conditions. But it is not statistically significant. A significant reduction of LZW is projected south of 10°N. This increase in wind speed over the south peninsular region and decrease over the northern region is expressed in all the models. However, the increase of wind over peninsular India is completely absent in the models CNRM-CM5 and CanESM2.

Fig. 7 depicts the number of active and break days during historical

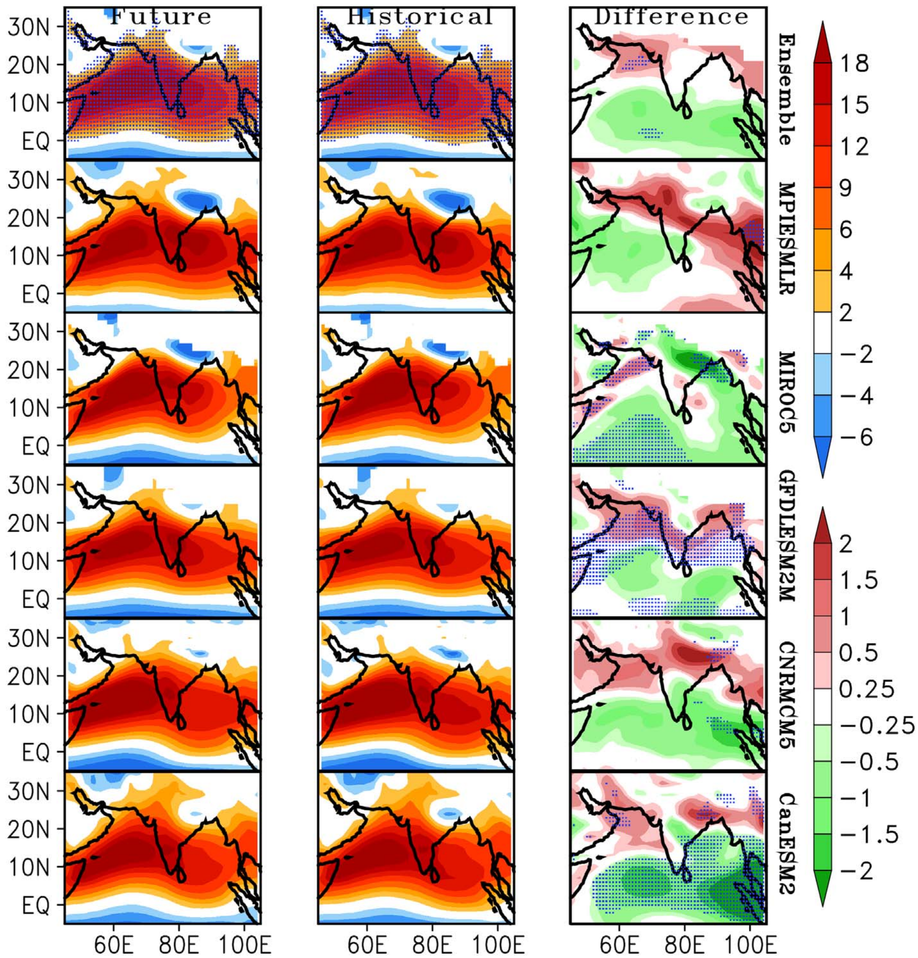

Fig. 5. Climatology of 850 hPa zonal wind ($m\ s^{-1}$) of ensemble and models during Active days. Future: 2080–2099, historical: 1986–2005, Difference: [U wind (future) – U wind (historical)]. Stippled pattern indicates significant area.

(1986–2005) and future (2080–2099) periods. In general, the mean number of active days during the peak monsoon months (July and August) is 10.1 days with a standard deviation of 2.3 days, however, the number of active days in the future projection is decreased to 8.7 days with a standard deviation of 2.5 days. Therefore, it can be concluded that the active days are decreasing at the end of the century. In the case of break days, a significant change is not observed between the historical and future projection periods. According to Gadgil and Joseph (2003), the duration of active and break spells controls the seasonal precipitation in a monsoon season.

3.4. Changes in intensity of short, medium and long spells

The duration and intensity of active and break phases of Indian summer monsoon have different time and intensity scales. Here, we classified active and break spells into short, medium and long spells as explained in the Data description and methodology section. The change in the intensity of ensemble mean LZW during different classes of active and break spells towards the end of the century is depicted in Fig. 8. Stippled pattern in the ensemble mean and in the difference indicates significant areas at 90% confidence level. The ensemble mean shows that during short active spells LZW has an increasing magnitude with about 1.5 $m\ s^{-1}$ indicating a positive trend of westerlies over the north Arabian Sea and northern parts of India. The LZW decreases to the south of 12°N as following the shift of LLJ to the north. During the medium active spells an intensification of LZW is seen at the northern west coast by about 1 $m\ s^{-1}$ and a weakening of LZW is seen at the monsoon core zone ($\sim 1\ m\ s^{-1}$). There is no significant change in LZW over peninsular India. However, a decrease in the LZW over the central and southern Arabian Sea is projected towards the future. The maximum decrease in LZW is over the equatorial Indian Ocean and the decrease (increase) over the south (north) of LLJ core indicates an overall shift of low level westerlies towards north. In the case of duration of short active, we noticed that the average number of spells is increasing slightly from 2.58 to 2.82 with standard deviations of 1.2 and 0.85, respectively. This lower value of standard deviation during the projection period indicates the lesser variability of short active while comparing to historical period.

A decrease in wind strength over the northeast regions of India is noticed during medium active conditions and this negative region moved further north in the case of long active spells. However, the Arabian Sea component of LZW shows an increase over the northern region and a decrease in the southern region of LLJ core. In the case of long active, decrease over the southern region is completely absent indicating the maintenance of wind speed over the region, however, over the northern parts of the Arabian Sea, the LZW shows a considerable increase. This shows a widening of low level westerlies over the region and it may increase the rainfall over the west coastal belts. In the case of long active spells, the average number of spells decreased to 2.8 from 4.3.

In the case of short breaks, the continental region does not show considerable change in the LZW towards the end of the century, however, a considerable weakening is projected to the south of 10°N. The medium break spells also follows a similar change with increasing zonal wind speed over the northern Arabian Sea and north India. The long break spells possess significant weakening of LZW over south of 10°N and central India. It is in accordance with the study by Sharmila et al. (2015) based on rainfall data from CMIP5. They indicated an intensification of both the extremes of wet and dry episodes in the future climate. They also projected enhanced propensity of short active and

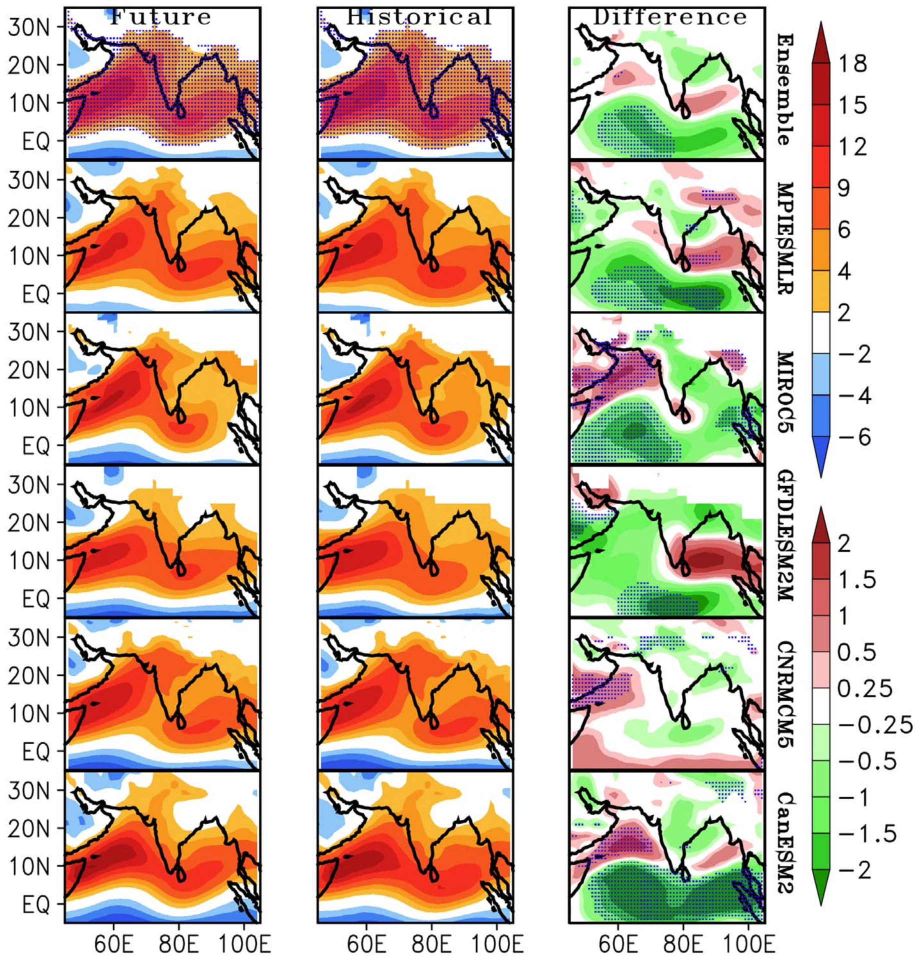

Fig. 6. Climatology of 850 hPa zonal wind (m s^{-1}) of ensemble and models during Break days. Future: 2080–2099, historical: 1986–2005, Difference: [U wind (future) – U wind (historical)].Stippled pattern indicates significant area.

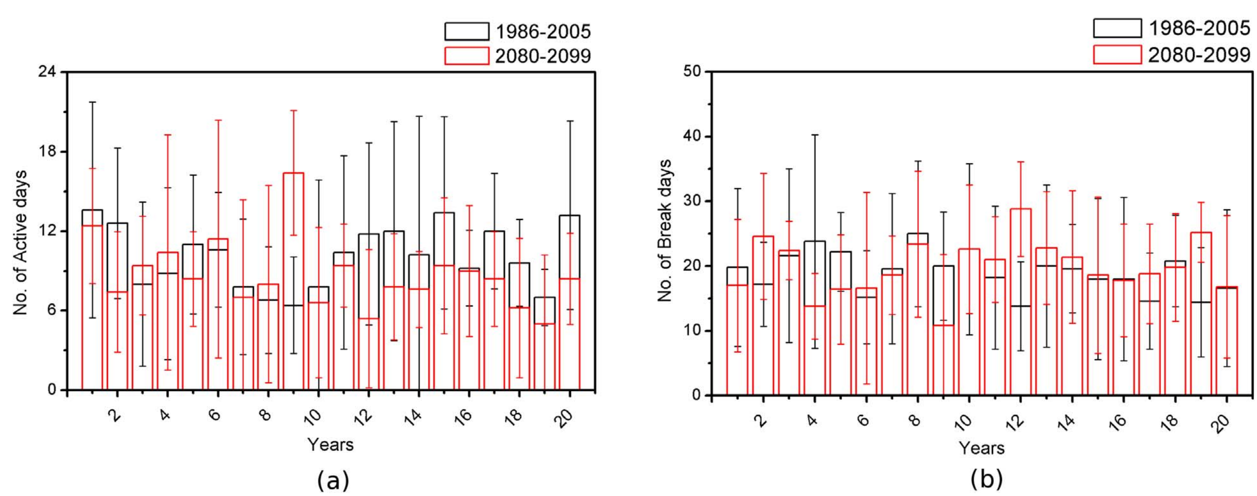

Fig. 7. Number of Active days (a) and Break days (b) during future (2080–2099) and Historical (1986–2005) years.

long break spells.

4. Summary and conclusions

Twenty CMIP5 models have been used to study the future changes in the ISM emphasising the changes in intensity and duration of active-break conditions based on the low level zonal circulation data set. Since earlier studies already pointed out the errors about the projection of rainfall by the CMIP5 models, we considered LZW as the parameter to study the changes in ISM activity at the end of the century. The models are compared with NCEP/NCAR reanalysis data based on spatial and temporal variations. The selected models are further filtered based on Taylor's diagram. Finally, five models have been selected for further studies, which effectively capture the LZW of monsoon and its sub-seasonal variation. The selected models are CanESM2, CNRM-CM5, GFDL-ESM2M, MIROC5 and MPI-ESM-LR. The future projection of ISM towards the end of the century is described using the ensemble mean of these selected models in RCP 4.5 scenario.

The LZW indicates a considerable increase (decrease) in magnitude of westerly wind at the north (south) of LLJ core. It is projected in

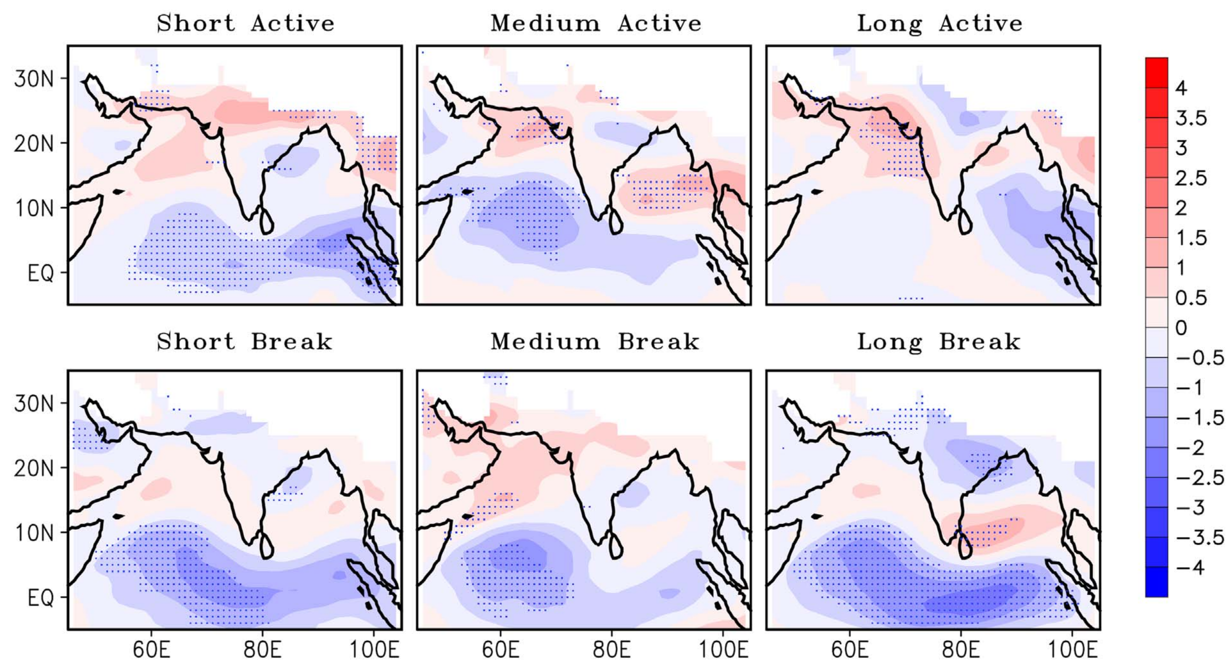

Fig. 8. Difference in ensemble model climatology of future (2080–2099) and Historical (1986–2005) 850 hPa zonal wind (m s^{-1}) during short, medium and long spells of active and break. [U wind (future) − U wind (historical)]. Stippled pattern indicates significant area.

mean, active and break phases of ISM. It proposes a shift of LLJ towards north from its current position. The strengthening of LZW at the northern west coast of India will provide more moisture and enhance the precipitation. At the same time weakening of LZW over the southern peninsular India lead to dry condition. A similar situation is noticed during active phase with higher intensity. The decrease of LZW over southern peninsula and an increase of LZW over north help in the generation of an anticyclonic vorticity over the southern peninsular region. This situation is not favourable for the formation of organized convections over the region, which enhances drying. In the case of break phases, models project a considerable strengthening which could provide some rainfall activity to the southern tip of peninsula, but the weakening of LZW over central and northern India could lead to intense break.

An increase in the average number of short active days with strengthening of LZW over north India is projected towards the future. It could bring more moisture (than that of in historical period) from the Arabian Sea to the north India regions during the short interval of time and cause intense rainfall activity over the region. It could lead to an increase the number of heavy rain events over the north India. A considerable decrease in the average number of long active days with increased rainfall activity at northern India is projected. The number of medium active days also decreases. That means the contribution of short and intense active spells will be more towards future. The break phase is more intense in the case of long break spells. It would adversely affect the agriculture sector of the country for which proper irrigation plans and policies may be planned. The number of break days does not possess any significant change. As a result the number of extreme events also would increase towards future with increase in intense rainy days and long dry days.

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